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Assessment of Acoustic Quality in Classrooms Based on Measurements, Perception and Noise Control

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1. Introduction

Education plays a fundamental role in the formation of modern society. The importance of education for humans is expressed thus by renowned Brazilian educator Paulo Freire[1]:
"The fountainhead of man's hope is the same as that of his educability: the incompleteness of his being of which he has become aware. It would be a sorry contradiction if, incomplete and aware of this incompleteness, man were not engaged in a permanent process of hopeful search. This process is education." (Freire, p 114)[1]
The long and arduous process of individual and collective education takes place primarily in classrooms. It is here that contact is established between teachers and students and between individual students and their peers. It is here that knowledge is transmitted in its most ancient form, i.e., through oral communication. The quality of this communication, and ultimately, of classroom education itself, is closely linked to the acoustic quality of the classroom. This acoustic quality can be characterized based on the reverberation time, speech transmission index, sound insulation, and the noise levels inside and outside the classroom[2-5]. High noise levels in the classroom impair oral communication, causing students to become tired sooner more often, and this premature fatigue tends to have a negative effect on their cognitive skills[6].
The reason for the existence of acoustic problems in classrooms, according to Seep[7], is not a lack of knowledge about how to solve the problem, but primarily a lack of sensitivity of the professionals involved, both in the field of teaching and that of classroom design, to solve the problem. The problem of acoustic quality in a classroom begins in its design phase and extends all the way to the final quality of the education provided in public and private schools, primary and secondary schools, and in universities.
Many of the aspects that appeared with the evolution of the modern era served to deteriorate the acoustic environment of the classroom. A reflection of our times is the fact that practically every student owns a mobile phone, a digital player, and other electronic devices that tend to render the school environment noisy, hindering its core purpose. Hagen[6] believe that the school environment should promote an atmosphere that encourages everyone's interest in listening and being involved in communication. An acoustically

comfortable environment should be one that provides everyone, individually and collectively, with the proper conditions to develop their skills.

This chapter presents an analysis of the acoustic quality of real classrooms based on *in situ* measurements and computer simulations of acoustic parameters such as Reverberation Time, Speech Transmission Index, Sound Insulation of Façades, and External and Internal Sound Pressure Levels. This chapter also discusses an assessment of the perception of teachers and students about the acoustic quality of the school environment.

Lastly, computer simulations were performed in order to identify, from the standpoint of noise control, what actions would be required to improve the acoustic quality of the evaluated classrooms.

2. Materials and methods

The present work involved an evaluation of the acoustic quality of real classrooms built according to standard designs. For this study, three design standards known as 010, 022 and 023 were selected (see description below). A total of six classrooms, two of each constructive design, were analyzed. To facilitate the identification of these schools, those of design 010 were dubbed C1 and C2, while those of design 022 were identified as C3 and C4, and those of design 023 as C5 and C6. The schools that participated in this evaluation were as follows: Standard 023 schools: 1) Colégio Estadual Walde Rosi Galvão and 2) Escola Estadual Luarlindo dos Reis Borges; Standard 022: 1) Colégio Paulo Freire and 2) Colégio Aníbal Khury Neto; and Standard 010: 1) Colégio Estadual Professor Alfredo Parodi and 2) Colégio Estadual Professora Luiza Ross. Physical aspects of the construction of the schools (choice of land and positioning of the buildings) were evaluated.

The results of this work were obtained by measuring the reverberation time (RT), sound insulation of classroom façades, and background noise (inside and outside the classrooms). In addition to these parameters obtained by measurements, the speech transmission index (STI) was obtained through the computer simulation of the calibrated models of the classrooms.

An investigation was also made of the users' perception of acoustic quality and comfort in the classrooms, based on questionnaires for students and teachers.

Noise control in the classrooms was investigated by means of computer simulations aimed at improving the acoustic quality of the classrooms by amending the insulation of their façades. Other simulations concentrated on observing the influence of the background noise level and reverberation time (RT) on the speech transmission index (STI).

2.1 Evaluation of reverberation time in classrooms

An important parameter affecting the acoustic quality of rooms is the RT. Each type of room (classrooms, theaters, churches) requires a given RT. Therefore, it is crucial that the RT be designed according to the purpose for which the room was conceived.

According to the ISO 3382-1[8] and ISO 3382-2[9], the RT can be measured by the interrupted noise method and by the integrated impulse response method. Measuring the RT by the interrupted noise method, as described in this chapter, consists of exciting the room with a pseudo-random pink noise and calculating the RT from the room's response to this excitation. A common setup to measure the RT by this method comprises: 1) an

omnidirectional sound source, 2) a sound power amplifier, 3) a noise generator, 4) omnidirectional microphones, and 5) a sound decay recorder and analyzer.
This chapter describes how the RT was measured with a dual-channel Brüel & Kjaer BK 2260 real-time sound analyzer, a BK 2716 power amplifier, a BK 4296 dodecahedron loudspeaker. The sound thus generated was captured by a microphone connected to the BK 2260 analyzer, which calculated the reverberation time for each frequency of the spectrum of interest. These measurements were then transferred to a computer using Brüel and Kjaer BK 7830 Qualifier software, which calculated the mean reverberation time of each classroom.

2.2 Evaluation of the sound insulation index of façades

The procedures for taking field measurements of sound insulation of façades are set forth in the ISO 140-5[10]. *In situ* measurements require the use of a flat cable to reduce the loss of sound energy through cracks in outside openings – windows or doors. Figure 1, below, shows in detail the use of a flat cable for measuring façade sound insulation.

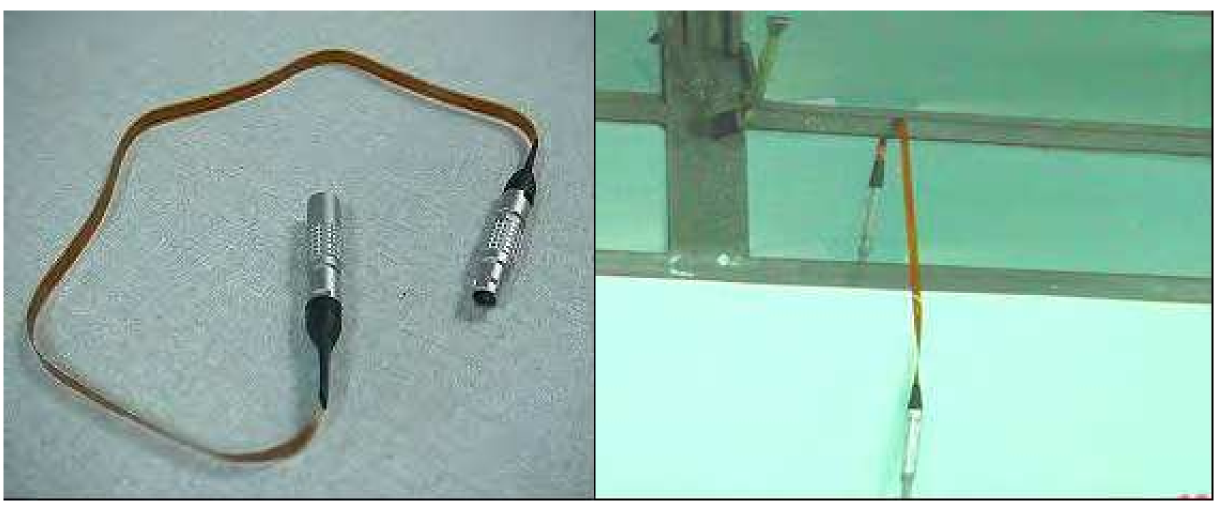


Fig. 1. Measurement of façade sound insulation using a flat cable

The sound insulation of a façade can be measured according to ISO 140-5[10], using a loudspeaker as the outdoor sound source. In this case, the subindex *ls* is used to characterize the loudspeaker in the measurement of the standardized level difference, $D_{ls,2m,nT}$, where $D_{ls,2m,nT,w}$ is the weighted standardized level difference corresponding to this method. The loudspeaker should be tilted at an angle of 45º, according to the ISO 140-5 standard. The loudspeaker in Figure 2 is connected to a noise generator.
Figure 2 illustrates the equipment required for measuring façade insulation using a loudspeaker as the sound source. The figure on the left shows the equipment positioned inside the classroom: a dual-channel sound analyzer, an omnidirectional loudspeaker and a microphone. The figure on the right shows the equipment positioned outside the classroom whose façade insulation is being evaluated: an external loudspeaker tilted at an angle of 45º and a noise generator.
The value of the weighted standardized level difference $D_{ls,2m,nT,w}$, which appears in the upper right-hand corner in Figure 3, can be calculated using the graphic method described

in ISO 717-1[11] and the BK 7830 Qualifier software. Since it is a single number, the value of $D_{ls,2m,nT,w}$ is used for comparison with the standardized values of reference to evaluate the performance of the building's façades in terms of sound insulation.

Fig. 2. Measurement of façade insulation according to ISO 140-5[10]

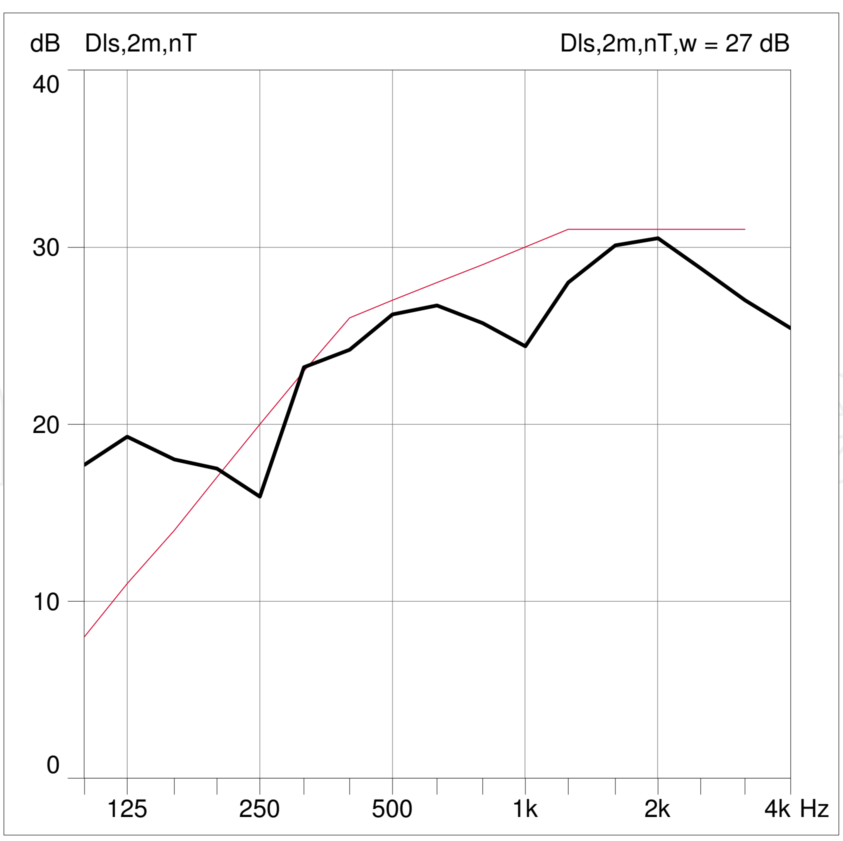


Fig. 3. Measurements of the standardized level difference $D_{ls,2m,nT}$ according to ISO 140-5[10]

The measured data can be expressed in a standard report according to ISO 140-5[10], which presents the value of the weighted standardized level difference $D_{ls,2m,nT,w}$. The standard report should also include the measurements in one-third octave bands of the values of the standardized level difference $D_{ls,2m,nT}$. The standard report is presented in Figure 4.

2.3 Evaluation of background noise in school environment

The sound pressure levels were determined from measurements taken inside the classrooms and in the surroundings of the schools. In both cases, the measurements were taken according to the Brazilian NBR 10151[12] standard, which regulates noise evaluations in inhabited areas for purposes of community comfort.

The purpose of measuring the surroundings was to evaluate the noise produced by the neighborhood (neighbors, street traffic, air traffic, industry, etc.), characterizing the regions where the schools are situated. As for the internal environment, the noise level in the classrooms was evaluated to verify if their acoustic quality favored the development of teaching-learning activities. The influence of noise produced in schoolyards and sports courts on the classrooms was also checked.

The number of samples from each school and the measuring time at each point were selected so as to allow for characterization of the noises of interest. In general, each evaluation involved measurements taken at three points, which resulted in an average value. The measuring time on the streets/roads around the schools was limited to 10 minutes at each point. The noise inside classrooms was assessed based on a 3-minute measurement at each point[4].

The sound pressures were measured with Brüel and Kjaer BK 2237 and BK 2238 sound level meters and the measured values were analyzed using Brüel and Kjaer BK 7820 Evaluator software.

2.4 Assessment of the speech transmission index STI

The STI is an acoustic descriptor that considers the effects of reverberation, background noise and the contribution of the direction of the source to determine speech intelligibility. These elements, which are usually treated individually, are combined in a single index[13,14].

The STI was simulated using Odeon 9.0 software[19]. This software uses the hybrid method to obtain the acoustic parameters. Rindel[15] claims that hybrid methods combine the best characteristics of the image source and ray tracing methods. A comparison of several computer simulation methods indicated that programs that use the hybrid method produce the best results[16].

The STI simulations were performed according to the IEC 60268-16[17] standard. To obtain acoustic parameters through simulations required first making a three-dimensional drawing of the room. Suitable calculation parameters were then inserted (such as the length of the impulse response), the characteristics of the finish surfaces (absorption and scattering coefficients) and the specifications of the sound source and receiver. For the source, the IEC 60268-16 standard establishes that it should be of the pointwise directional type, in order to simulate the characteristics of the human mouth. The noise generated by the source should simulate both the timbre and volume of the human voice.

Standardized Level Difference according to ISO 140-5

Field measurements of airborne sound insulation of facade elements and facades

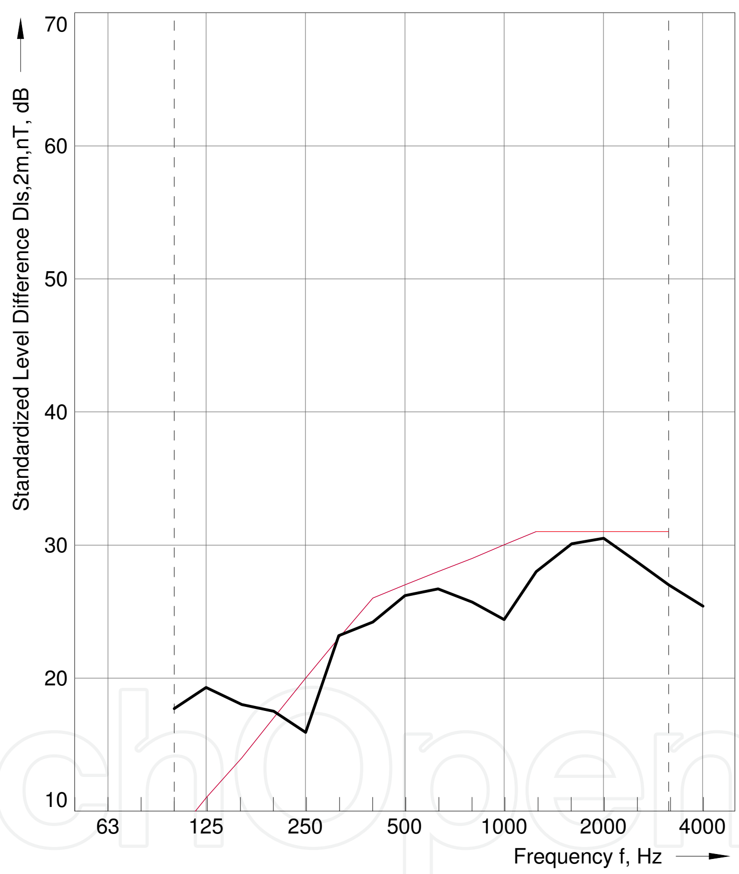
Client: Date of test: 08/12/2005

Description and identification of the building construction and test arrangement:

Area S of test specimen: 17,00 m²
Receiving room volume: 120,00 m³

- - - - Frequency range according to the
—— curve of reference values (ISO 717-1)

Frequency f Hz	Dls,2m,nT 1/3 Octave dB
50	
63	
80	
100	17,7
125	19,3
160	18,0
200	17,5
250	15,9
315	23,2
400	24,2
500	26,2
630	26,7
800	25,7
1000	24,4
1250	28,0
1600	30,1
2000	30,5
2500	28,8
3150	27,0
4000	25,4
5000	



Rating according to ISO 717-1

$D_{ls,2m,nT,w}\,(C;C_{tr})$ = 27 (-1; -3) dB

Evaluation based on field measurement results obtained by an engineering method

No. of test report: Name of test institute:

Date: 08/12/2005 Signature:

Fig. 4. Measurement report according to ISO 140-5[10] and ISO 717-1[11] – Field measurement of airborne sound insulation of building façades

The three-dimensional models were calibrated based on a comparison of the values of measured and simulated RT. The values of sound pressure level in octave band frequency measured inside a classroom were then inserted in the calibrated model, and the loudspeaker and microphone positions were defined. A 0.50x0.50 m grid was defined for the loudspeakers, and the microphone was placed in the typical position of the teacher and directed towards the students.

2.5 Noise control in classrooms

The simulations of acoustic improvements were performed in two stages: 1) improvement of façade insulation; and 2) improvement of the acoustic conditioning of the classrooms.

The simulations of improved façade insulation were performed using Bastian 2.3 software and the parameter evaluated was the weighted standardized level difference $D_{ls,2m,nT,w}$ (ISO 140-5[10]). The calculations of insulation using Bastian software were based on parts 1 to 3 of the European Standard series EN 12354[18]. The modifications implemented in the simulations considered the alteration of the material and type of window in the classroom façade.

Odeon 9.0[19] software was used to simulate improvements in the acoustic conditioning inside the classrooms, and the parameters evaluated were the RT and the STI. Changes in the finishing material of the rooms' ceilings and in background noise levels were simulated.

2.6 Subjective assessment

To evaluate teachers and students' perception of noise in schools, questionnaires were designed for each group. These questionnaires were based on similar studies conducted by Dockrell et al.[20], Loro[21], Losso[22], Enmarker and Boman[23], and Dockrell and Shield[24].

After validating the questionnaires in a pilot test, they were applied to 71 teachers and 1080 students of the public school system. The questionnaires were applied to the students in the classrooms. The questions were read out loud one by one by the researcher, who allowed sufficient time for the students to write down their answers. As for the teachers, they were given an explanation about the objective of the research and about the design of the questionnaire, after which they answered it individually without the researcher's help.

Out of the total of 1080 questionnaires distributed to the students, 1035 were considered valid. The students' questionnaire contained closed questions and were answered by 5th to 8th grade schoolchildren aged 9 to 18. In the teachers' questionnaire, the answers were given in the form of scores ranging from 0 to 3. The 71 questionnaires distributed to the teachers were all validated.

The data obtained from the students' questionnaire was analyzed statistically following two strategies. The first strategy involved a descriptive analysis using contingency tables, showing the frequency of the individuals' responses as a function of two qualitative variables[34,35]. These tables were the first descriptive instrument for drawing up two hypotheses, whose general formulation is given by: a) hypothesis H0: the two factors are not associated; and b) H1: the two factors are associated[34,35]. The second strategy consisted of using statistical tests of hypotheses that verified the significance of the link between different factors. The R software developed by the R Development Core Team[25] was used to calculate the association tests.

The hypotheses outlined during the first analytical strategy were verified by the Q and Qp statistics, whose approximate probability distribution is the chi-square[34,35]. The decisions about the hypotheses were taken at a 95% level of confidence. In some situations where the expected frequencies in the cells of the contingency table were low, the approximation of the chi-square distribution for the Q and Qp statistics was compromised, so an alternative test was applied[34,35]. In this case, the choice fell on Fisher's Exact Test[34,35].

The analysis of the questionnaire applied to the teachers was similar to that of the students, but the Qs statistics was used for the tests of association. The Qs statistics is used when one of the variables of the contingency table presents an ordinal measure[34,35] (which is the case of the questionnaire applied to the teachers, whose answers were given scores of 0 to 3).

3. Constructive designs of the classrooms

The classrooms in the public schools evaluated here are designed in standard modules that are adjustable to the need for new schools, depending on the forecasted number of students and the type of terrain where they are to be constructed.

The characteristics of the construction designs selected were as follows. 1) Design 010, which consists of independent blocks with a central circulation area and classrooms arranged on both sides of a hall (Figure 5); 2) Design 022, comprising classroom blocks arranged side by side without a hall between them (Figure 6); and 3) Design 023, similar to design 010, composed of independent blocks of classrooms arranged on the two sides of a central hall (Figure 7).

Table 1 presents the characteristics of the classrooms: volume, material of the walls, floor and ceiling and type of window.

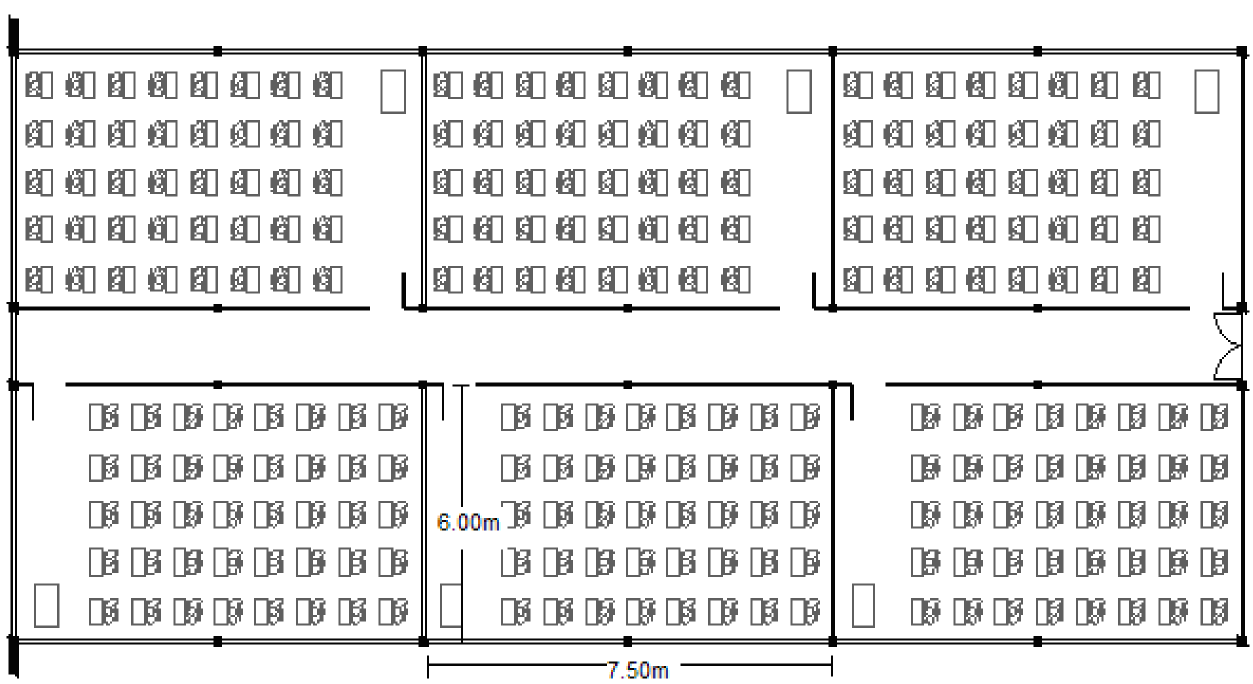


Fig. 5. Classroom construction design 010

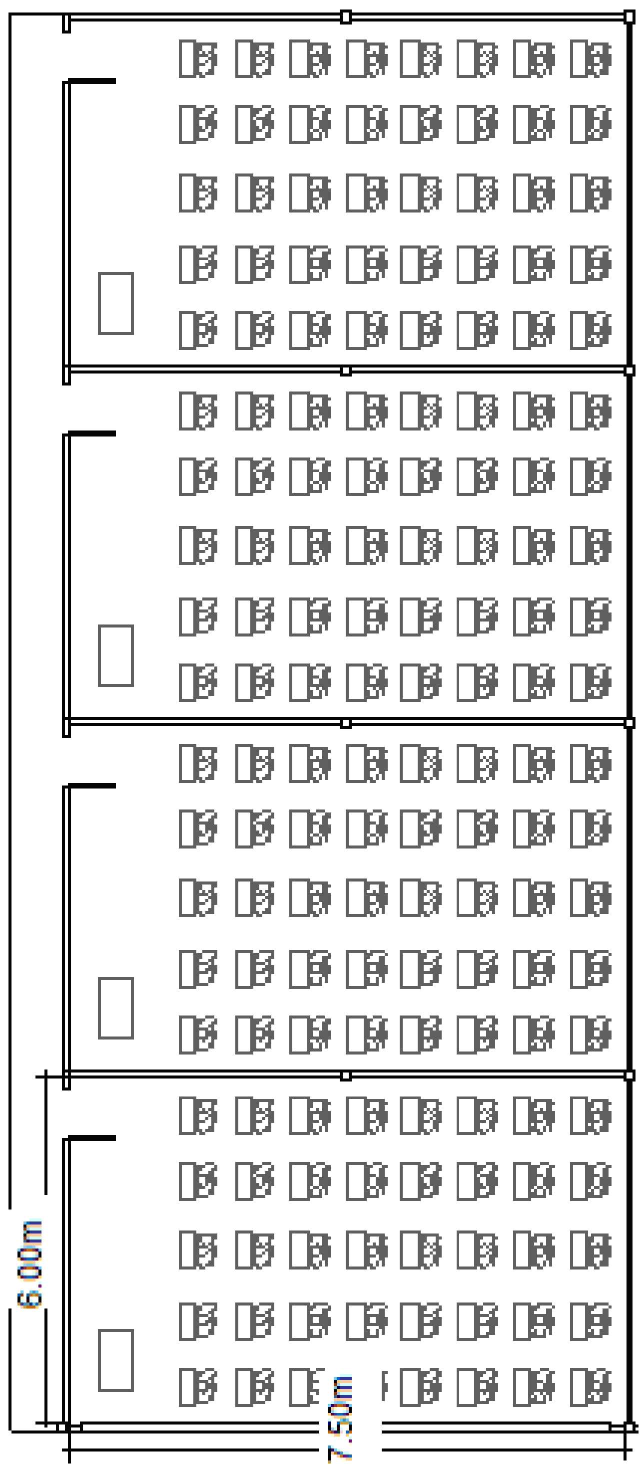


Fig. 6. Classroom construction design 022

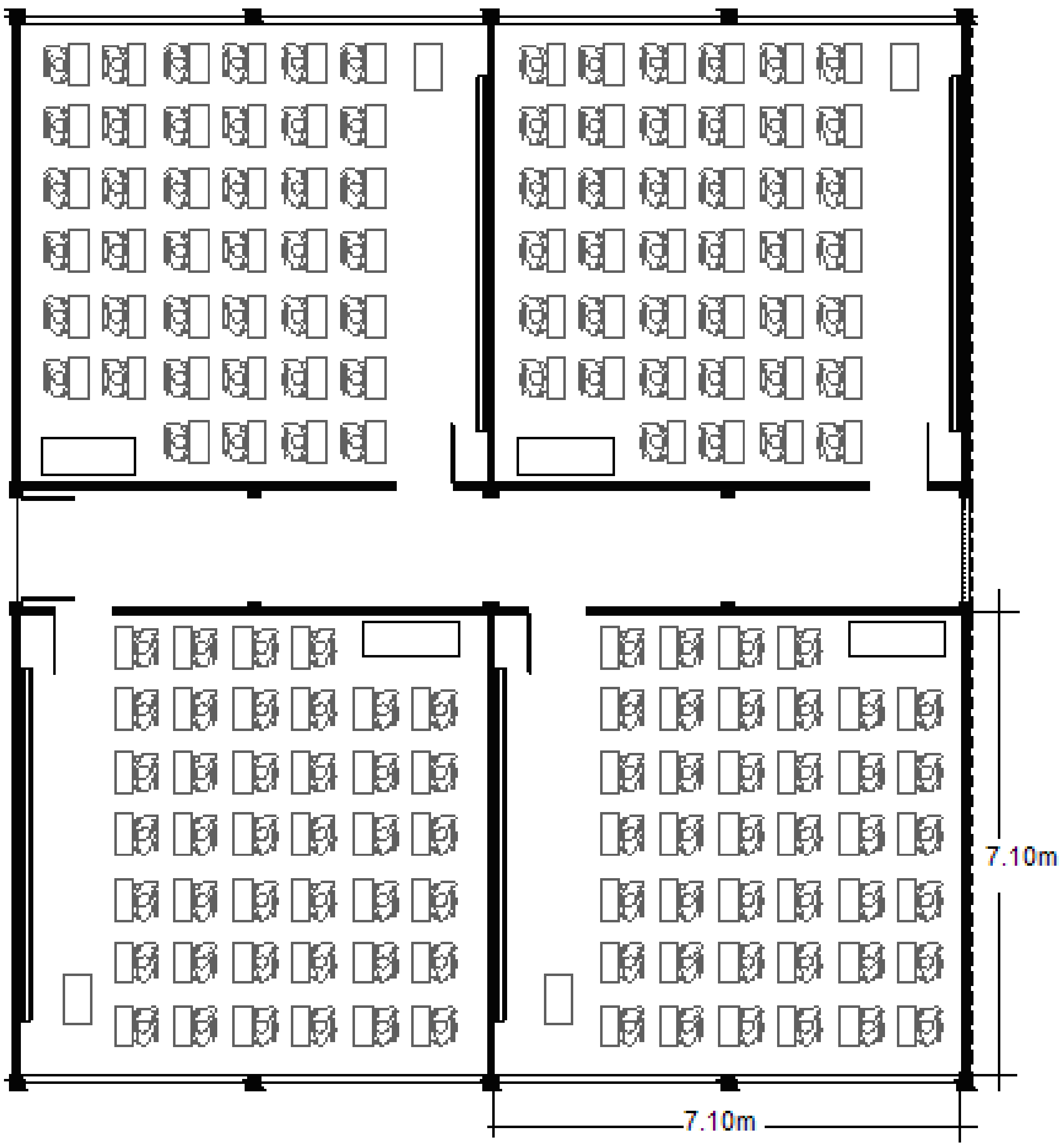


Fig. 7. Classroom construction design 023

Classroom construction designs	Volume (m^3)	Wall material	Floor material	Ceiling material	Type of window
010	139	Ordinary brickwork	Parquet	Wood paneled ceiling	Iron window frames with glass panes
022	139	Ordinary brickwork	Parquet	Concrete slab	Iron window frames with glass panes
023	156	Ordinary brickwork	Ceramic tiles	Concrete slab	Iron window frames with glass panes

Table 1. Construction characteristics of the classrooms

4. Results of the measurements and discussion

The schools selected for this study were built during three distinct periods. The schools built to design 010 went up in 1977 (C1) and 1978 (C2). The two schools built according to design 022 were concluded in 1998 (C3 and C4), while those of design 023 were built in 2001 (C5) and 2005 (C6).

4.1 Background noise inside and outside the classrooms

To evaluate the acoustic composition of the classroom environment, measurements were taken of the equivalent sound pressure levels L_{eq} expressed in dB(A). Firstly, the external environment was assessed based on measurements taken on the sidewalks around the schools, at the distances established by the Brazilian standard NBR 10151[26].
The purpose of evaluating the external environment is to check if there is any influence of traffic noise in the classrooms. This evaluation enabled us to investigate the first aspect relating to the location of the schools: the choice of terrain.
According to the Brazilian NBR 10151[26] standard, which establishes sound levels for external environments, the maximum L_{Aeq} admissible for school zones during the daytime is 50 dB. Table 2 presents the average values of the sound levels measured in the proximities of the classrooms[4].

Classroom	Construction Design	L_{eq} dB(A)	Permissible limit for environmental noise Brazilian NBR 10151 standard[26] dB(A)
C1	010	66.3	**50**
C2	010	66.2	
C3	022	68.4	
C4	022	60.5	
C5	023	59.2	
C6	023	51.8	

Table 2. Traffic noise in the proximities of the classrooms

The values listed in the above table indicate that classroom C5 and C6 of design 023 and classroom C4 (design 022) are located in quieter zones than the other schools. The values measured in all the schools' surroundings were higher than those established by the Brazilian NBR 10151 standard[4,26].
Although the surrounding noise exceeds the limit established by the Brazilian standard, during the field measurements it was found that the traffic noise did not contribute significantly to the composition of background noise in the classrooms. This was confirmed by the sound levels obtained from the other measurements taken inside the schools, as well as by the subjective assessment.
The subjective assessment revealed that, when questioned about the origin of the most disruptive noises in the classroom, 83% of the students considered that the noise coming from inside the classroom itself was worse. Noises generated in the other school environments, such as halls, adjacent classrooms and schoolyards, were cited by 15% of the

interviewees. Only 2% of the students mentioned noises coming from outside the school (cars, neighbors, factories, etc.).
The teachers' perception about the origin of the noises that are most disruptive in the classroom coincided with that of the students. Table 3 lists the results of the question asked of the teachers concerning the most disruptive noises in the classroom.

Origin of the noise	Average score
Students in the classroom	2.2
Adjacent classrooms, halls, and schoolyards	1.6
External sources (cars, neighbors, factories, etc.)	0.8

Table 3. Origin of the most disruptive noises, in the teachers' opinion

The teachers' answers in the questionnaire were given in the form of scores varying from 0 to 3 (0 = nothing, 1 = a little, 2 = more or less, 3 = a lot). Table 3 lists the mean scores for each answer. As can be seen, the noises from the schools' surroundings scored lowest among the three choices. Apart from presenting the lowest score, the value of 0.8 indicates that the influence of external sources is negligible.
The analysis of the questionnaires revealed that the most disruptive noises in the classroom come from the school itself, and are completely unrelated to external noises.
As for the acoustic measurements, an example confirming the non-influence of noise from the external surroundings was obtained in classroom C3 (design 022). Although traffic noise in this school exceeds the limit established by the Brazilian standard, our investigations revealed that this noise does not interfere in the classrooms. This statement was confirmed by the noise levels measured during the school vacations, when the school was empty. The noise levels measured in the schoolyard and classroom were, respectively, L_{eq} = 52.3 dB(A) and L_{eq} = 40.4 dB(A). This sound level in the classroom is in line with that recommended by the NBR 10152 standard, which establishes a level of 40 dB(A) for acoustic comfort in classrooms. The noise levels measured here suggest that the condition of acoustic comfort is achieved when the school is empty, i.e., when the noise produced in the surroundings does not impair the acoustic comfort of the classrooms.
The data presented above confirm the correct choice of terrain for the location and construction of the schools. The only exception was classroom C6, where it was found that, although the noise from surrounding traffic is low, another annoying external factor is the proximity of the railway line, Figure 8. The noise levels emitted by the train were measured in the schoolyard close to the classroom blocks. The L_{eq} measured as the train passed by the school, Figure 9, was 71.8 dB(A), with a minimum and maximum of 64.3 dB(A) and 80.8 dB(A), respectively. According to the NBR 10152 standard, the noise level in schoolyards should range from 45 to 55 dB(A). Figure 9 shows the cursor at the frequency of 1000 Hz, for which L_{eq} = 67 dB(A), L_{Max} = 72.2 dB(A) and L_{Min} = 60.4 dB(A).
The passing train generates a very high noise level, contributing significantly to the increase in the background noise inside the classrooms. The school's proximity to the railway line (Figure 8) indicates the inappropriateness of the land for the construction of classroom C6.

Fig. 8. Classroom C6 and the railroad traffic

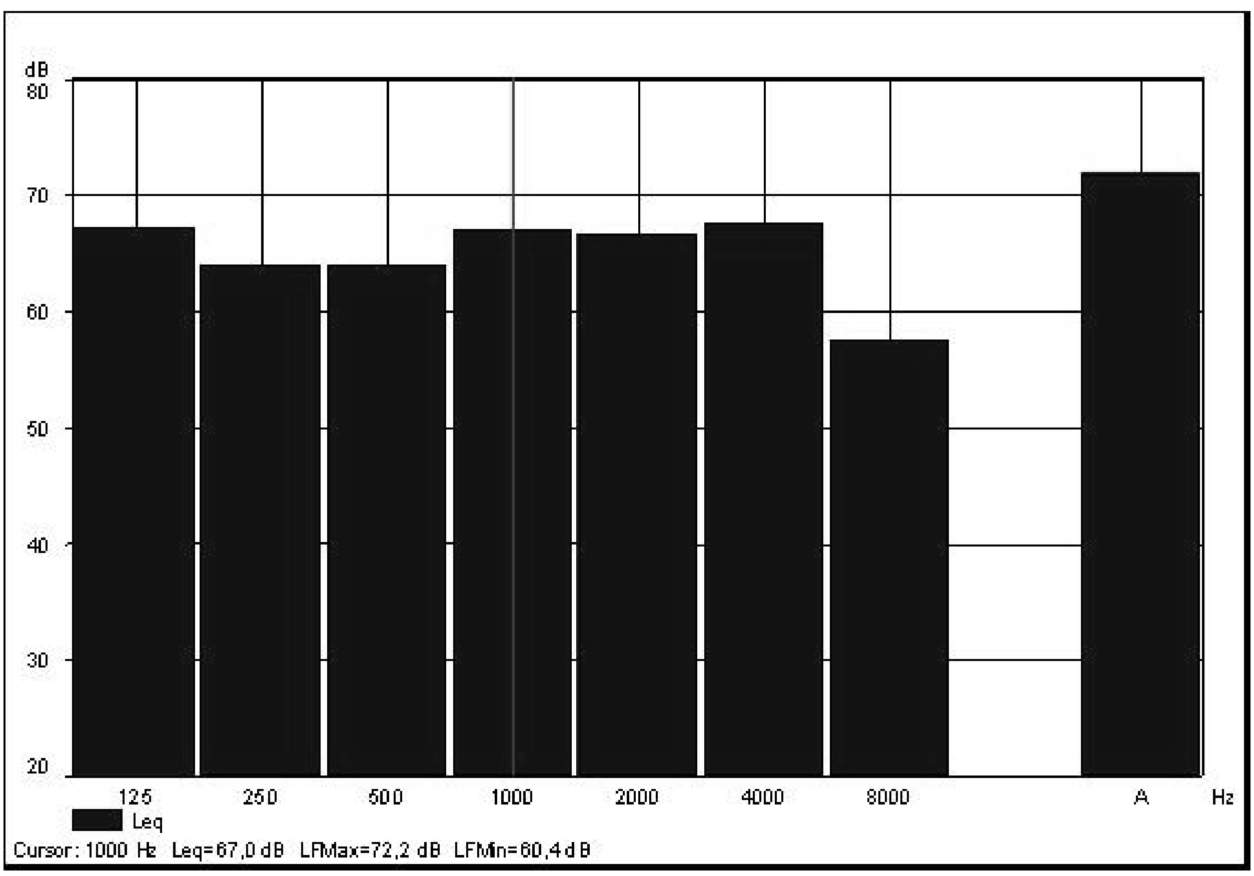


Fig. 9. Frequency analysis of railroad noise in the vicinity of classroom C6

With regard to the internal environment, the background noise in the classroom was investigated. To this end, the background noise originating from classes held in the other classrooms of the same block was measured in an empty classroom. The purpose of these measurements was to ascertain if the noises produced in a classroom affect other classrooms around it.

To determine the daily reality, all the measurements were taken with the windows open, seeking to interfere as little as possible in the schools' daily routines. Some situations could therefore not be evaluated in the same way. This was the case of classroom C3, where it was impossible to evaluate how the noise produced in each classroom affected the other classrooms because the noise coming from the schoolyard exceeded that of adjoining classrooms. Table 4[4] shows the noise levels measured in the empty classroom with the adjoining classrooms engaged in standard activities.

<table>
<tr><th>Classroom</th><th>Construction Design</th><th>L_{eq}
dB(A)</th><th>Limit for acoustic comfort
Brazilian
NBR 10152 standard[14]
L_{eq}
dB(A)</th></tr>
<tr><td>C1</td><td>10</td><td>59.4</td><td rowspan="5">40 - 50
*40 dB(A) is a comfortable noise level in classrooms
**50 dB(A) is an acceptable noise level for classroom purposes</td></tr>
<tr><td>C2</td><td>10</td><td>63.2</td></tr>
<tr><td>C4</td><td>22</td><td>51.1</td></tr>
<tr><td>C5</td><td>23</td><td>59.1</td></tr>
<tr><td>C6</td><td>23</td><td>60.7</td></tr>
</table>

Table 4. Equivalent sound pressure levels L_{eq} in five empty classrooms with the other rooms engaged

The NBR 10152 standard establishes 40 dB(A) as a comfortable noise level in classrooms, although 50 dB(A) is acceptable for classroom purposes. As can be seen in the above table, the noise levels far exceed the limit determined by this standard. According to the World Health Organization[27], excessive noise levels affect not only the quality of verbal communication but also lead to serious problems in the student's intellectual development, such as slow language learning, difficulties in written and oral language, limitations in reading skills and in the composition of vocabulary.

With regard to the levels listed in Table 4, it can be concluded that the classrooms assessed here have a negative effect on each other, generating high levels of background noise that are incompatible with the values established by the Brazilian standard for acoustic comfort in classrooms. Additional disruptive noise originates from physical education activities. The classrooms of school design standards 010 and 022 showed insufficient distance between the classrooms and schoolyards and sports courts. Figure 10 illustrates this proximity between schoolyards and classrooms C2 (design 010) and C3 (design 022). The figure clearly shows the classroom windows in both schools facing the schoolyard, which contributes to increase the background noise inside the classrooms.

(a) Classroom C2 – design 010

(b) Classroom C3 – design 022

Fig. 10. Proximity between classrooms and schoolyards

Table 5 lists the values measured during physical education activities. These measurements were taken in empty classrooms with open windows[4].

Classroom	Construction Design	Equivalent Sound Pressure Level L_{eq} dB(A)
C1	10	66.7
C2	10	66.0
C3	22	74.6
C4	22	62.5

Table 5. Noise levels in empty classrooms during phys ed activities

The noise levels produced during physical education classes are high. The close proximity of classrooms to the schoolyard where these activities take place is extremely detrimental to the teaching-learning process, not only because of the noise levels that impair speech intelligibility but also due to the students' distraction and diminished concentration resulting from the visual stimuli provided by phys ed activities right outside the classroom windows. The noise levels shown in Table 5 and the photographs in Figure 10 reveal a serious problem in the layout of school spaces, since noisy environments should be far away from the environments that require silence, which is the case of classrooms.

Because the sound levels proved incompatible with the necessary conditions of acoustic quality and comfort in the classroom, the equivalent sound pressure levels were measured during a Portuguese language class (classroom C3) and a mathematics class (classroom C6). The values measured were L_{eq} = 74 dB(A) for the Portuguese language class and L_{eq} = 73.7 dB(A) for the mathematics class and corresponded mainly to the teacher's voice during explanatory classes when the students simply listened[4]. These values are high and demonstrate the vocal effort required of the teachers. This effort is even greater when phys ed activities are being held in the schoolyards, because they raise the noise level inside the classrooms.

The subjective research involving the teachers confirms the measured results. It was found that 21% of the interviewed teachers have had to take a leave of absence from teaching due to noise-related health problems, the main reason being vocal fatigue.
Table 6 shows the results of the teachers' subjective assessment of how noise affects them. The main aspects the teachers listed were the need to raise their tone of voice (2.5), overall fatigue (2), and vocal fatigue (2).

	Average score
Difficulty to concentrate	1.6
Headache	1.5
Irritability	1.9
Overall fatigue	2.0
Buzzing in the ears	1.2
Raising the tone of voice	2.5
Vocal fatigue	2.0

Table 6. Influence of noise in the classroom in the teacher's opinion.

According to Lubman and Sutherland[2], the cost of vocal fatigue of schoolteachers in the United States is US$ 648 million per year. In Brazil there are no estimates of this cost. However, as can be seen in Table 6, the need for teachers to raise their voices is high (2.5), regardless of the schools where they teach (Qs = 6.244, p-value = 0.182).
Noise in the classroom does not affect only teachers, for the findings of the subjective assessment revealed that it disturbs 92% of the students. The activities that suffer the most from noise-related disruption are listening to the teacher's explanations (46%), reading (23%), and doing exams (23%). According to the teachers, noise strongly affects the students' scholastic performance (score = 2.3).
These findings confirm that unfavorable acoustic conditions in the classroom make teaching and learning unnecessarily exhausting for everyone involved in the process[6].
In addition to the noise levels in empty classrooms, the noise level in the halls of the Luiza Ross School (C2) was measured. The measured L_{Aeq} was 72.9 dB with a maximum of 88.4 dB(A) and a minimum of 59.3 dB(A). For school halls, the NBR 10152 standard establishes a noise level of 45 dB(A) for acoustic comfort and 55 dB(A) as acceptable for this purpose. The levels measured in the Luiza Ross School far exceeded the acceptable level.
Another very important environment in the school is the library, where silence is essential and the noise level should be kept below 40 dB(A) (Knudsen and Harris[32]). The library at Luiz Ross (C2) is located in the same block as the classrooms, with windows high up in the wall looking out onto the hall and the entry door facing the outside of the block. The L_{eq} measured in the library was 64.3 dB(A), with a maximum of 75.7 dB(A) and a minimum of 54.7 dB(A). The NBR 10152 standard establishes 45 dB(A) as the noise level for acoustic comfort in libraries, accepting a limit of up to 55 dB(A). The level of 64.3 dB(A) measured in the library far exceeds the upper limit of the standard, impairing aspects inherent to these spaces, such as concentration and reading[6].

4.2 Reverberation time in classrooms

Reverberation time is an extremely important descriptor of the acoustic quality of a room, and several national and/or international standards establish reference values for the RT in rooms. With regard to classrooms, various acoustic standards present reference values for the RT that should be observed in the design of the classroom. Germany, Japan, the United Kingdom, the United States of America, Portugal and France have specific technical standards for evaluating the RT of classrooms.

In Japan, RT values represent the average in 2-octave bands including 500 Hz and 1000 Hz, and RT is measured in the furnished and unoccupied classroom[28]. In the USA, RT is given as the maximum RT for mid-band frequencies of 500 Hz, 1000 Hz and 2000 Hz, and RT is measured in the furnished and unoccupied classroom (ANSI S12.60[29]). In Germany, the DIN 18041[30] standard establishes that RT values represent the average in 2-octave bands including 500 Hz and 1000 Hz, and RT is measured in the furnished and occupied classroom. The German standard DIN 18041:2004 recommends that, in general, the RT of an unoccupied classroom should not be more than 0.2 s above the required value listed in Table 7. In France, RT is calculated as the arithmetic mean, for furnished and unoccupied classrooms, of the values measured at the frequencies of 500 Hz, 1000 Hz and 2000 Hz (WHO[27]), and in Portugal (also furnished and unoccupied classrooms), the RT recommended for classrooms is established as a function of two frequency ranges: 1) 125 Hz $\leq f \leq$ 250 Hz, and 2) 500 Hz $\leq f \leq$ 4000 Hz (WHO[27]). The World Health Organization – WHO recommends the value of 0.6 s for the RT in classrooms (Shield and Dockrell[31]). Table 7 (Zannin et al.[5]) shows the RT recommended in different countries as a function of the volume of the classroom.

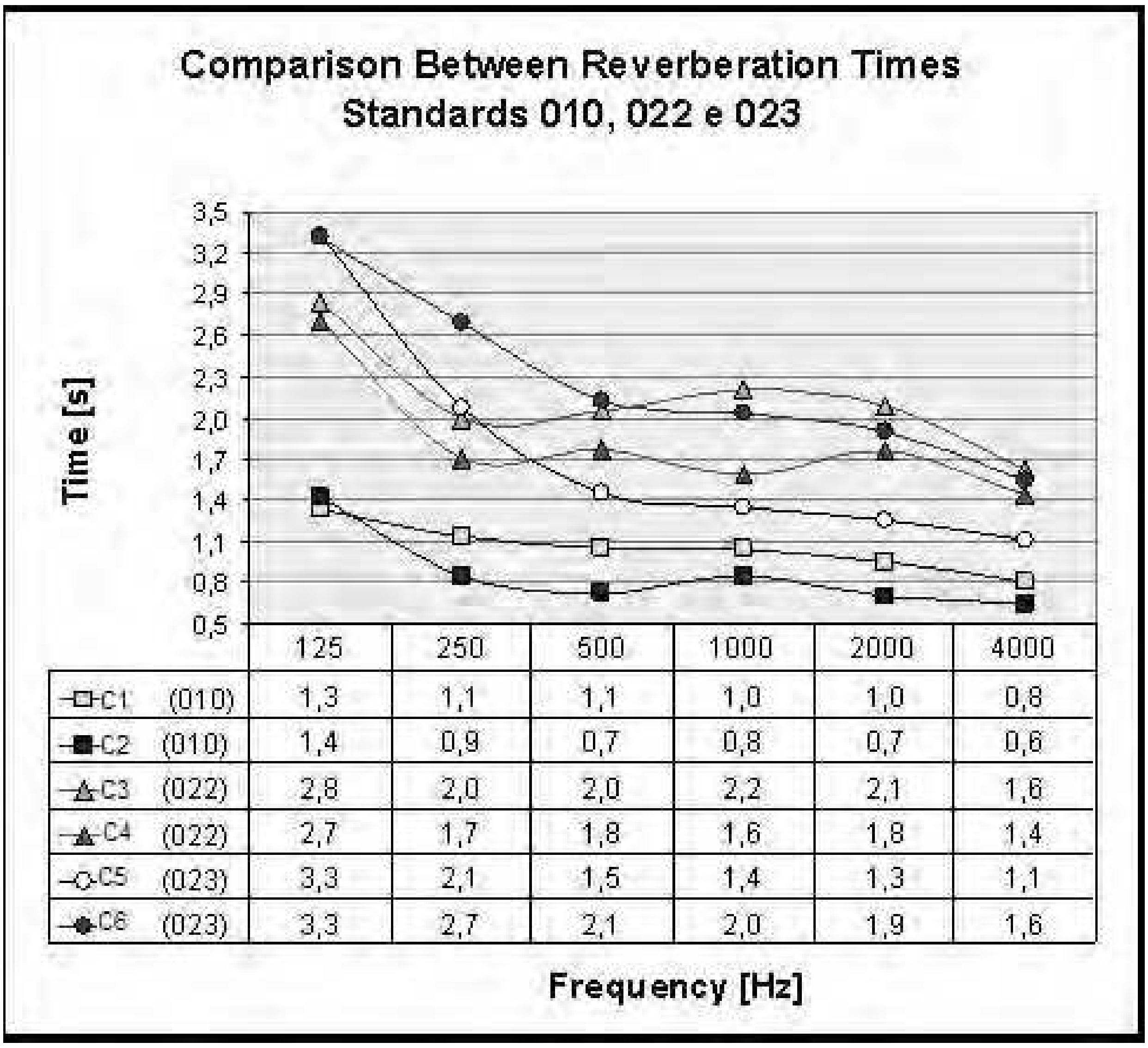
Country	Reverberation Time RT, in [s]	Volume V, in [m³]
France	$0.4 < RT \leq 0.8$	$V \leq 250$
	$0.6 < RT \leq 1.2$	$V > 250$
Germany	RT = 0.5	V = 125
	RT = 0.6	V = 250
	RT = 0.7	V = 500
	RT = 0.8	V = 750
Japan	RT = 0.6	V ~ 200
	RT = 0.7	V ~ 300
Portugal	$RT \leq 1.0$ - for 125 Hz $\leq f \leq$ 250 Hz	-
	$0.6 \leq RT \leq 0.8$ - for 500 Hz $\leq f \leq$ 4000 Hz	-
United States of America	RT = 0.6	$V \leq 283$
	RT = 0.7	$283 < V \leq 566$
WHO	RT = 0.6	-

Table 7. Recommended Reverberation Time for Classrooms in different countries

Reverberation time was measured in furnished and unoccupied classrooms, and is listed in Table 8.

Construction Design of the School	Volume of the Classroom [m³]	Maximum Classroom Capacity
010	139	40 students
022	139	40 students
023	156	40 students

Table 8. Characteristics of the classrooms: Volume and Capacity



	125	250	500	1000	2000	4000
C1 (010)	1,3	1,1	1,1	1,0	1,0	0,8
C2 (010)	1,4	0,9	0,7	0,8	0,7	0,6
C3 (022)	2,8	2,0	2,0	2,2	2,1	1,6
C4 (022)	2,7	1,7	1,8	1,6	1,8	1,4
C5 (023)	3,3	2,1	1,5	1,4	1,3	1,1
C6 (023)	3,3	2,7	2,1	2,0	1,9	1,6

Fig. 11. Reverberation time of the six classrooms measured according to the ISO 3382-2 standard

Note that the RTs of all the classrooms evaluated here exceed the 0.6 s limit established by the ANSI S12.60[29] and Japanese standards. When compared with the French recommendation cited by WHO[27], only classroom C2 (design 010) falls within the established range of 0.4 to 0.8 s, since the mean RT at frequencies of 500, 1000 and 2000 Hz was 0.73 s in this classroom. Only classroom C2 with a mean RT of 0.75 s, at frequencies of 500 and 1000 Hz, complies with the range of values recommended by the DIN 18041[30] standard for furnished unoccupied classrooms.

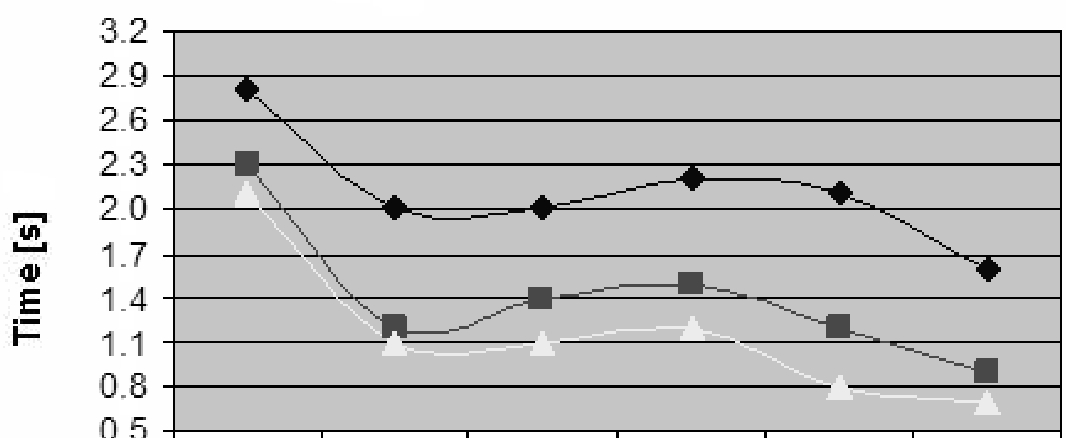
The differences in the RTs of the constructive designs are due to the different finishing materials employed (Table 1). In the classrooms of design 010, the floors are made of parquet and the ceiling is paneled in wood. The 022 design also has parquet floors, while the 023 design has ceramic tile floors. The ceilings of designs 022 and 023 are not paneled, but simply plastered and painted. The walls of all the constructive designs have painted plaster overlays[4].

The classrooms of design 010 were built about 20 years before those of designs 022 and 023, and their interior finishing (walls, floors and ceilings) and RTs offer better acoustic conditions than do the classrooms in the newer buildings. This is attributed to the low sound absorption coefficients of the interior finishes currently in use.

The RTs measured in all the classrooms showed the lack of acoustic comfort in the classrooms, except for classroom C2. The acoustic deficiency of these spaces impairs communication between students and teachers, since high reverberation times diminish the intelligibility of speech[4,5].

In one of the evaluated classrooms, classroom C3 of construction design 022, the RT measurements were taken considering three different situations of occupancy: a) unoccupied and furnished, b) with 50% occupancy, or 20 students, and c) with 100% occupancy, or 40 students. Figure 12 shows the measured RTs as a function of occupancy.

Figure 12 clearly illustrates the influence of occupancy in the reduction of RT. A comparison of the situation of the unoccupied room and the situation of 100% occupancy indicated that this reduction in RT varied from 0.7s at a frequency of 125 Hz to 1.3s at a frequency of 2000 Hz. Even with full occupancy, the classroom did not reach the RT specified by any of the recommendations listed in Table 7. This demonstrates the urgent need for changes in the interior design of this classroom, using sound absorbing materials whose effect is to reduce the RT, thus contributing to improve its acoustic quality.



	125	250	500	1000	2000	4000
RT empty	2.8	2.0	2.0	2.2	2.1	1.6
RT 50%	2.3	1.2	1.4	1.5	1.2	0.9
RT 100%	2.1	1.1	1.1	1.2	0.8	0.7

Frequency [Hz]

Fig. 12. Influence of classroom occupancy on reverberation time

4.3 Speech transmission index – STI

To obtain objective data on the speech intelligibility in the classrooms, acoustic simulations of the STI were performed using Odeon 9.0 software[19]. The 3D models were calibrated by comparing the measured and simulated RTs.

To simulate the STI, data on the room's background noise must be inserted in the computer model. In these simulations, the background noise was inserted according to the frequency spectrum measured in a classroom (see Figure 13), which is equivalent to a sound pressure level of approximately 60 dB(A).

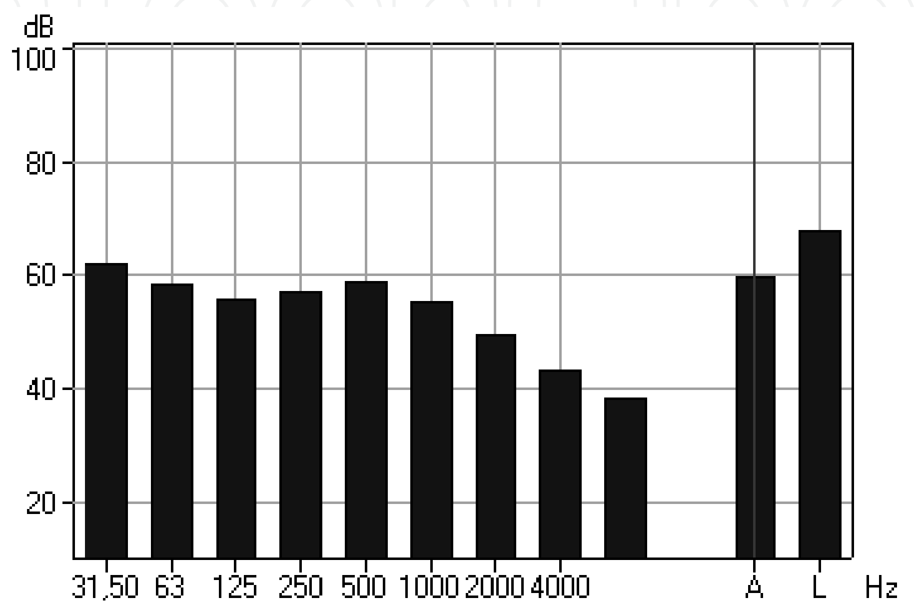


Fig. 13. L_{Leq} graph in octave bands measured in a classroom and used in the simulation of the STI

The maps below present the simulation of the STI in the three construction designs under study.

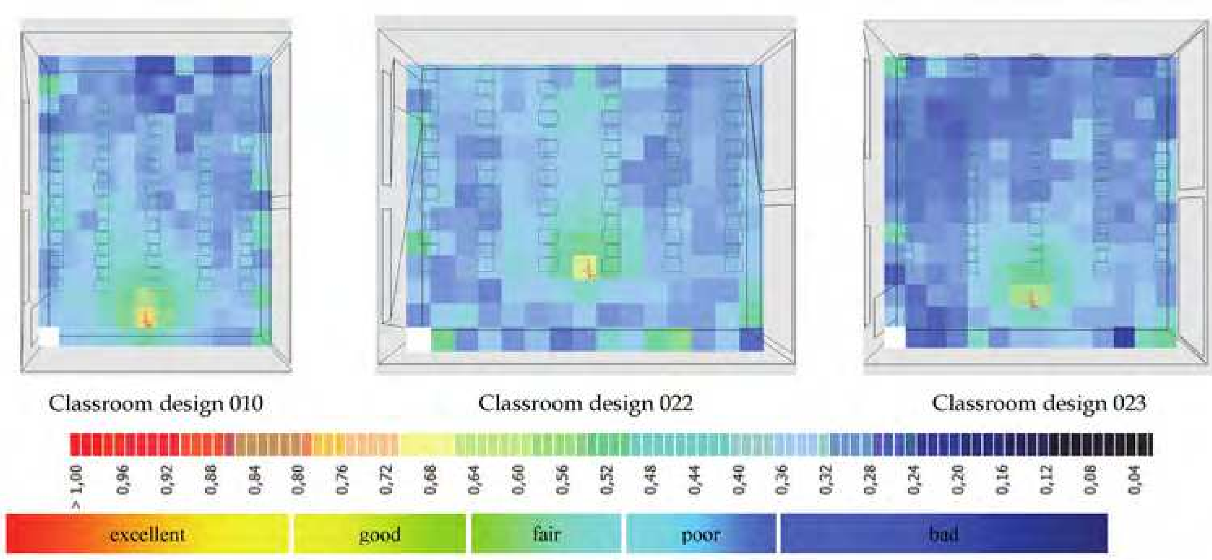


Fig. 14. Simulation of the STI in the construction models under study. The subjective scale equivalent to the objective values of STI are in line with the IEC 60268- 16:2003 standard. The red dot represents the sound source.

As can be seen in the STI maps (Figure 14), the speech intelligibility at most of the simulated points in the classrooms varies from "fair" to "bad," according to the subjective scale of the IEC 60268- 16:2003 standard.

4.4 Façade sound insulation

Sound insulation should be a priority in school environments where the sources of noise cannot be altered, especially in schools affected by high levels of noise from road, air and railroad traffic. Another important factor is the sound insulation between quiet and very noisy spaces, as in the case of the school designs 010 and 022, where phys ed classes are held in schoolyards located very close to the classrooms.

Due to the complexity of the measuring process in terms of the amount of equipment and number of people involved, sound insulation measurements were taken in only one classroom of each design.

The façades of the classrooms blocks of school design 010 are composed of ordinary brickwork overlaid with mortar, inside and outside, and painted. The windows are made of iron frames and ordinary glass panes. Figure 15 shows the façades of this construction design. The evaluations of façade insulation of design 010 were carried out at the Alfredo Parodi School (C1).

The measurements of sound insulation of the classrooms of design 023 were carried out at the Luarlindo dos Reis Borges School (C6). The façades of this design are composed of ordinary brick walls overlaid with ceramic tile, while the inside is overlaid with mortar and painted. The iron frame windows have ordinary glass panes. Figure 16 shows the façade of the Luarlindo dos Reis Borges School during the measuring procedures.

Fig. 15. Classroom Façades of the Luiza Ross and Alfredo Parodi Schools

Fig. 16. Measurement of the sound insulation of the façade according to ISO 140-5[10] (Luarlindo dos Reis Borges School)

The evaluation of sound insulation of the schools of design 022 was carried out at the Anibal Khury Neto School (C3). As Figure 17 indicates, the classroom blocks have different façades on each side, one containing doors and the other windows.

Fig. 17. Façade of a classroom – left: Door and Walls; right: Wall and Windows

Classroom	Construction Design	$D_{ls,2m,nT,w}$ [dB]	Façade Sound Insulation Brazilian NBR 15575 standard[33] [dB]
C1- Alfredo Parodi School	010	21	**25 – 29**
C3 - Aníbal Khury Neto School	022	31	
C6 – Luarlindo dos Reis Borges School	023	27	

Table 9. Sound insulation of classroom façades

Table 9 indicates that only one of the three classrooms evaluated does not meet the requirements of the Brazilian NBR 15575[33] standard. In fact, one of the classrooms has a higher sound insulation index than recommended by the standard. However, it should be kept in mind that most classrooms have their windows open while they are in use, due to the ambient temperature and the need for air circulation. The sound insulation measurements were taken with the windows and doors closed. Therefore, it is to be expected that the values of sound insulation of the façades are very different from the values measured in ideal conditions. Another point that should be considered is the state of conservation of the buildings, which directly affects their sound insulation. Figure 18 shows a classroom with broken window panes and large spaces between the door and the floor, which are factors that contribute to reduce the sound insulation.

Fig. 18. Classroom com broken window panes and spaces between the door and the floor

4.5 Noise control in classrooms

Based on the objective and subjective evaluations carried out in this study, it can be concluded that there are difficulties in spoken communication between teacher and student inside the classrooms. This is due to the high background noise and inadequate RT, particularly in the classrooms of school design standards 022 and 023, which generate "fair" to "bad" speech intelligibility (Figure 14) according to the subjective scale of the IEC 60268-16:2003 standard.

Because the quality of spoken communication is an extremely important factor for learning in classrooms, acoustic simulations were performed which aimed at improving this quality in the rooms under study. Using Bastian software, changes in the façade construction elements were simulated to obtain the $D_{ls,2m,nT,w}$. In addition, changes in the absorption coefficient of the ceiling finishing material and the background noise were simulated to obtain the RT and STI inside the classrooms, using Odeon software.

4.5.1 Simulations of sound insulation

To study the improvements in sound insulation, simulations were performed by changing the type of window used in the façade. The windows in the evaluated rooms consist of poorly sealed iron window frames and ordinary glass panes. For these simulations, a window contained in the library of the Bastian software[18,36] was used, which is well sealed and double paned – 4 mm + 12 mm + 4 mm (two 4 mm glass panes with 12 mm or air between them).

The table below presents the values of $D_{ls,2m,nT,w}$ measured in the classrooms and simulated using Bastian software.

Standard Classroom	Measured Sound Insulation $D_{ls,2m,nT,w}$ [dB]	Simulated Sound Insulation $D_{ls,2m,nT,w}$ [dB]
010	21	44
022	31	44
023	27	45

Table 10. Sound insulation measured *in situ* and simulated with changed window element

Table 10 shows the improvement in the sound insulation of the classroom façades attained by replacing the existing windows for better sealed windows with double panes.

Any improvement in the sound insulation of façades means a reduction of the background noise inside the classroom, especially in areas with intense external noise. This reduction in background noise translates into improved acoustic quality inside the classroom.

It should be kept in mind that, in the cases studied here, due to the climatic conditions and also in view of the need for air circulation, the classrooms usually have their windows open when in use. The measurements and simulations considered closed windows.

4.5.2 Simulations of reverberation and speech intelligibility

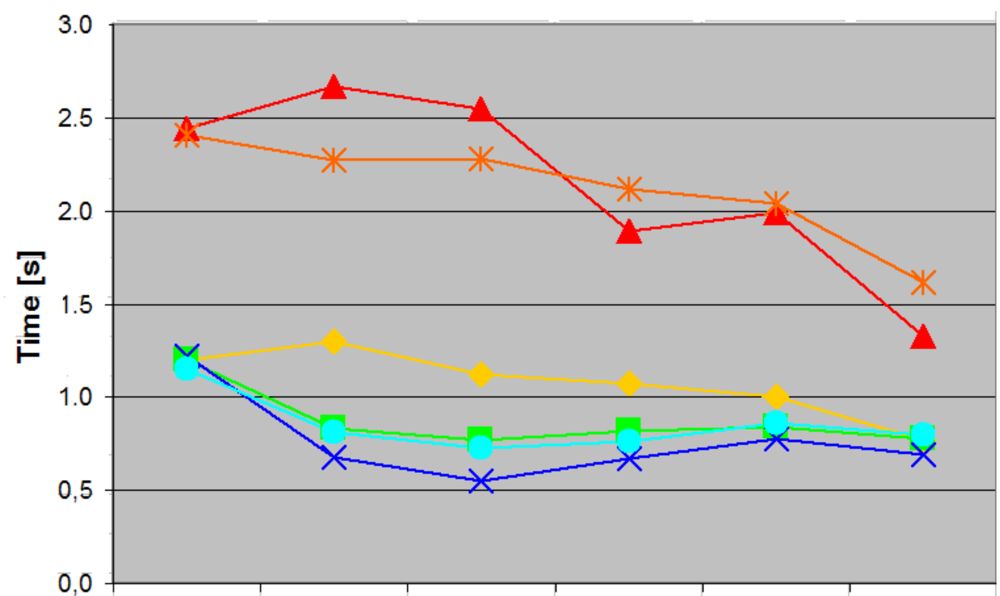
The reverberation time in a room is related to the absorption coefficient of the materials that cover the surfaces of the room. Therefore, the RT simulations were performed by replacing the ceiling finishing material of the rooms for another with a higher absorption coefficient.

Table 11 presents, in octave band frequency, the absorption coefficients of the ceiling finishing materials in the rooms and used in the simulations. In construction design 010, the ceiling is wood paneled, while the rooms of designs 022 and 023 are devoid of ceiling finishing material, consisting simply of concrete slabs. A fiberglass acoustic ceiling board was used in the simulations.

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Wood	0.25	0.25	0.30	0.40	0.40	0.55	0.60	0.60
Concrete	0.018	0.018	0.02	0.03	0.03	0.03	0.03	0.03
Fiberglass	0.33	0.33	0.79	0.99	0.91	0.76	0.64	0.64

Table 11. Absorption coefficient of the ceiling materials in the classrooms and used in the acoustic simulations

Figure 19 shows the RT simulated with the existing ceilings in the classrooms and with the fiberglass acoustic ceiling.



		125	250	500	1000	2000	4000
Design 010	current	1,2	1.3	1.1	1.1	1.0	0,8
	amended	1,2	0.8	0,8	0,8	0,8	0,8
Design 022	current	2,4	2,7	2,6	1,9	2,0	1.3
	amended	1,2	0,7	0,6	0,7	0,8	0,7
Design 023	current	2,4	2,3	2,3	2,1	2,0	1.6
	amended	1,2	0,8	0,7	0,8	0,9	0,8

Fig. 19. Reverberation time simulated in the real conditions of the classroom (current) and with amended ceiling material

As can be seen in Figure 19, there is a significant decrease in the values of RT, especially in the classrooms of design standards 022 and 023, which have no type of ceiling finishing.
If one compares the values of simulated RT (Figure 19) against the values of RT established by various standards (Table 7), one finds that, upon amending the ceiling material, all the rooms are considered suitable according to the French standard. Comparing the simulated RT with the German standard, only the classroom of the 010 model remains inadequate even after replacing the ceiling material, although the RT values are very close to those stipulated by this standard. With regard to the other standards listed in Table 7, the modified rooms presented a mean RT of 0.1s to 0.2s higher than that established by these standards.
In addition to the RT, the STI was simulated with amended ceiling finish. Two sound pressure levels (34 and 60 dBA) were used for the background noise, which were measured in classrooms. The graph in Figure 20 presents a frequency spectrum of the background noise of 34 dB(A).

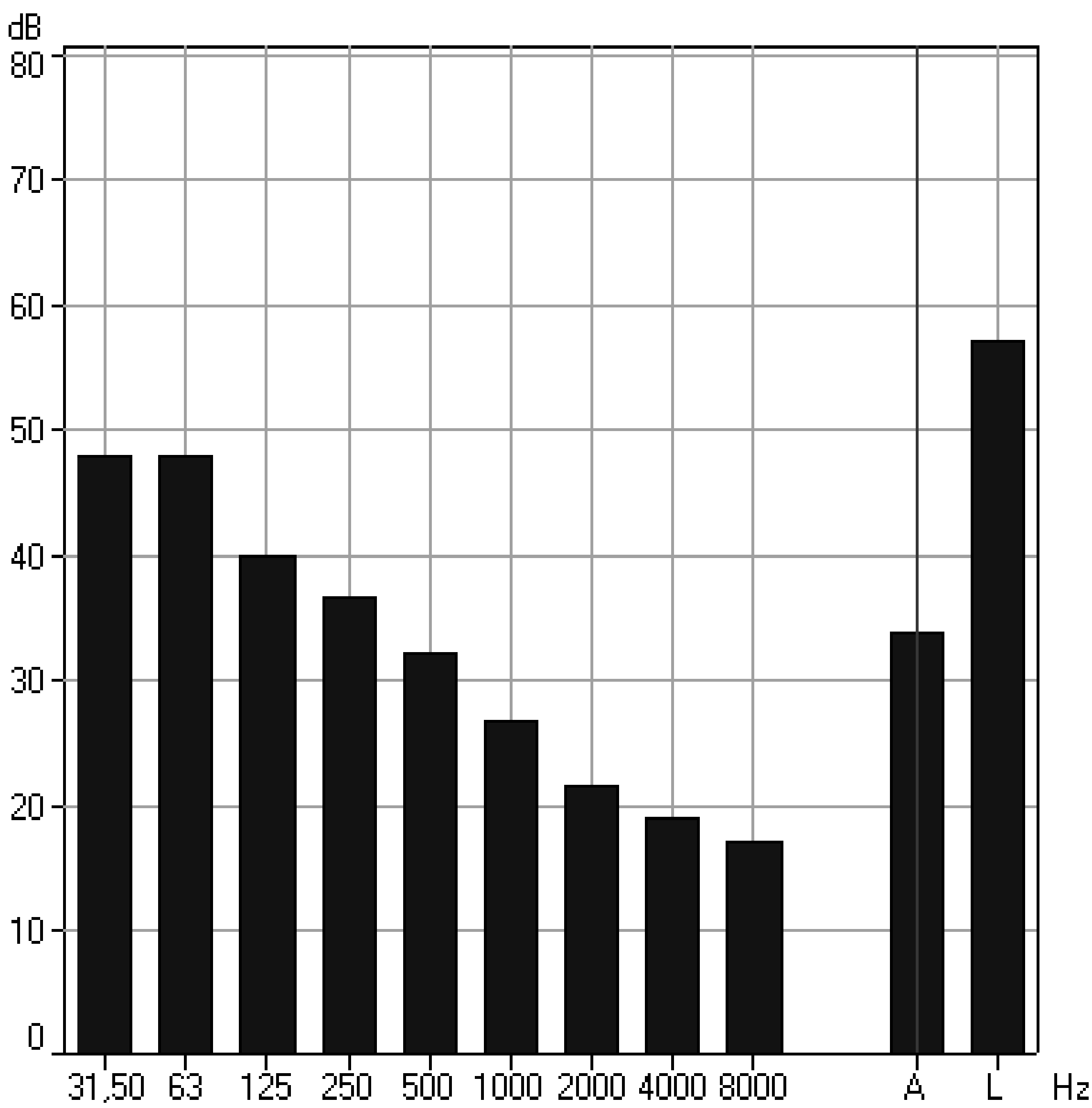


Fig. 20. Non-weighted frequency spectrum of background noise of 34 dB(A)

The figures below present the STI maps of the design standards 010, 022 and 023, for two background noise levels (60 and 34 dBA) and two situations of RT (current situation and situation with amended ceiling material).

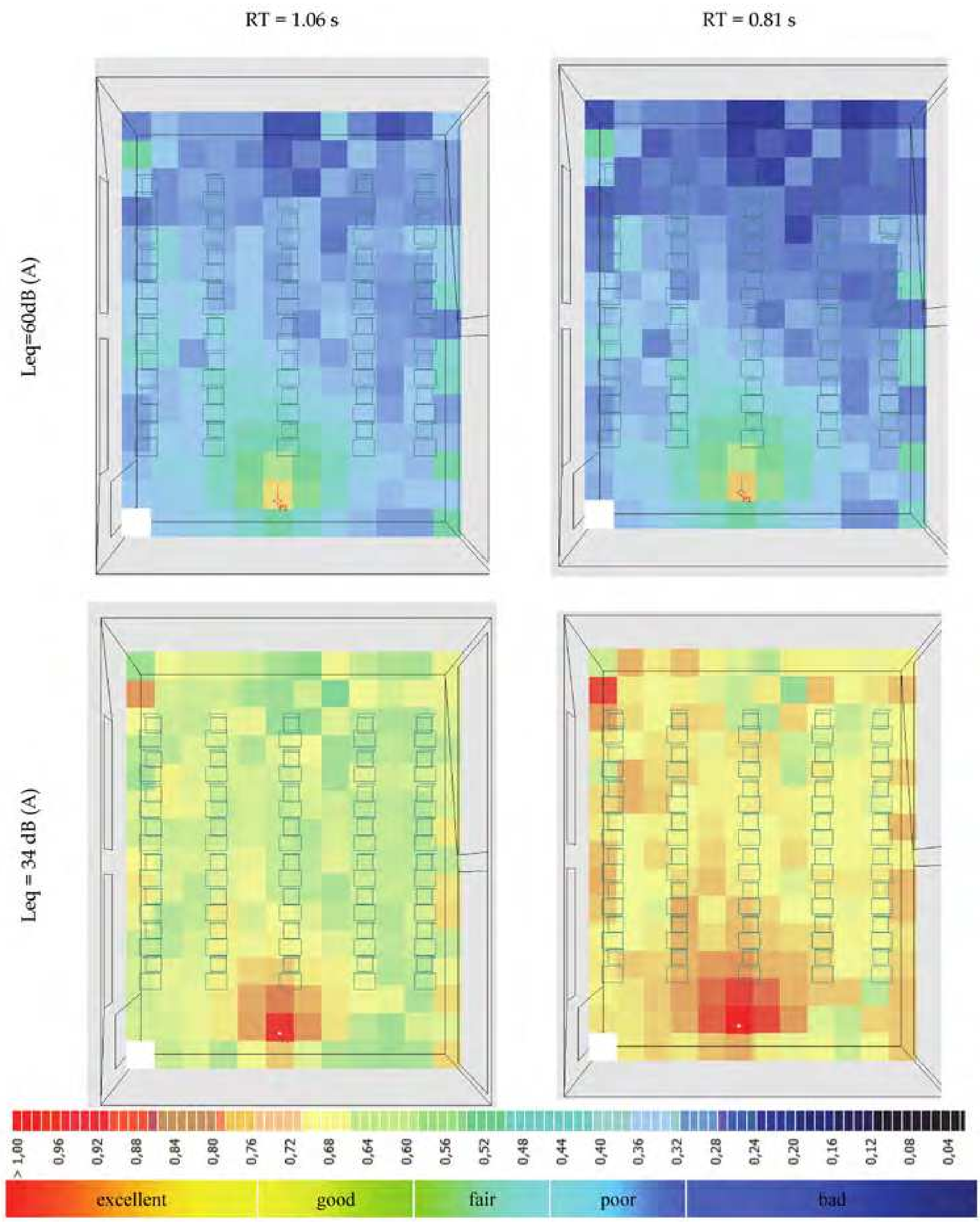


Fig. 21. STI simulations in the classroom of design standard 010. The red dot represents the sound source and the red line indicates its direction (towards the students)

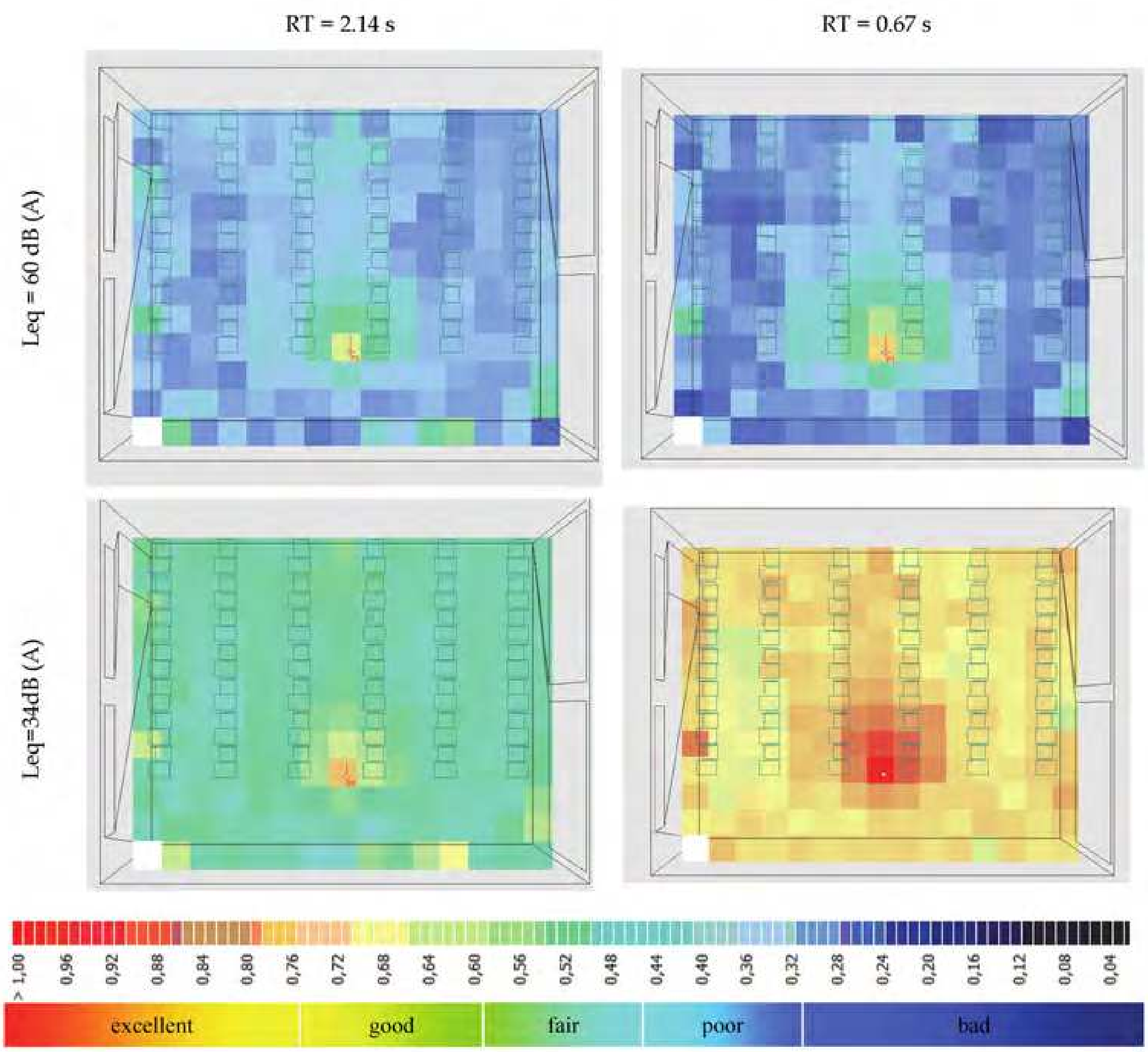


Fig. 22. STI simulations in the classroom of design standard 022. The red dot represents the sound source and the red line indicates its direction (towards the students)

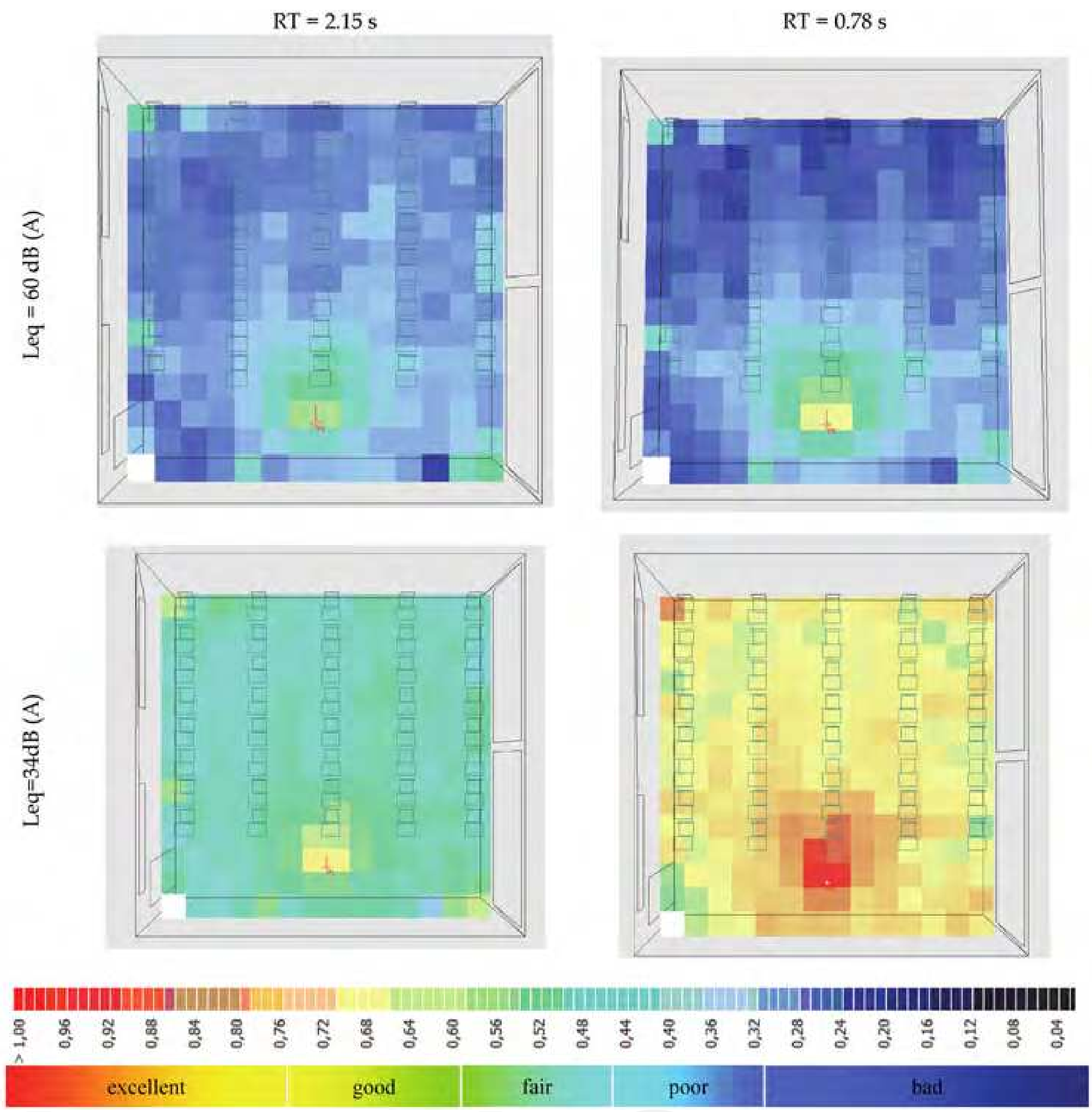


Fig. 23. STI simulations in the classroom of design standard 023. The red dot represents the sound source and the red line indicates its direction (towards the students)

Figures 21, 22 and 23 present the STI simulation maps of the classrooms of design standards 010, 022 and 023. The map in the first column and first line of the figures represents the current situation of the classrooms in terms of RT and SPL.

The maps in the second column and first line represent the simulation with reduction of the RT by replacement of the current ceiling finishing material by a material with higher acoustic absorption, and maintenance of the background noise at 60 dB(A). A comparison of these maps with the current situation indicates that the STI worsened at the points located farther away from the sound source, thus classifying these points as having "bad" to "poor" intelligibility.

The maps on the second line and first column in Figures 21, 22 and 23 represent the STI for the current situation of RT in the classrooms, with reduced background noise. These maps show a significant improvement in speech intelligibility, particularly the room of design standard 010, whose RT was lower than that of the other classrooms. For this room, the map in this situation

generated a "good" to "excellent" STI. For the rooms of design standards 022 and 023, the speech intelligibility in this situation of RT and SPL is classified as "fair" to "good."
The maps presented in the second column and second line of Figures 21, 22 and 23 show "good" to "excellent" STI for all the rooms under study. This situation is characterized by low background noise and adequate reverberation time.

5. Conclusions

The results of the measurements presented here indicate that the evaluated classrooms do not offer adequate acoustic comfort for the development of educational activities.
Aspects of location and construction involved ascertaining the choice of terrain where the schools are located and the position, or layout, of the schools' recreational areas. The six schools in question were found to be located in regions where the levels of traffic noise are not bothersome inside the classrooms. This situation indicates the correct choice of land for five of the six schools assessed. The exception is classroom C6, which is located adjacent to a railway line. The levels of background noise measured in the classrooms, halls and libraries were higher than recommended by the NBR 10152 standard.
The RTs measured in all the classrooms showed the lack of acoustic comfort in the classrooms, with the exception of classroom C2. An analysis was also made of the influence of occupancy on the RT, based on one of the rooms with the longest reverberation times. Despite the significant reduction in RT with the room at 100% occupancy, it was found that even with the reduction of 0.9 to 1.3 s in the range of frequencies between 500 and 4000 Hz, the room still did not present values compatible with those recommended by the standards cited in Table 7.
Based on the STI simulations, it was found that the speech intelligibility in the classrooms is classified as "fair" to "bad." These simulations indicated the lack of speech intelligibility even at desks located close to the teacher/speaker.
The subjective assessment indicated that both students and teachers perceive noise in the classroom and are bothered by it. According to the teachers, noise is a factor that negatively affects teaching and learning.
Most of the students stated they could hear the teacher well. However, they considered the classrooms noisy and stated that the activity of listening was the most affected. This statement was confirmed by the results of the questionnaire which the teachers answered.
The results of the measurements and the questionnaires revealed that the noise that impairs classroom activities comes from the school itself, not only from adjacent classrooms, halls and schoolyards but also, and mainly, from inside the classroom itself.
The subjective research involving the teachers confirmed the measured results. It was found that 21% of the interviewed teachers have had to take a leave of absence from teaching due to noise-related health problems, the main reason being vocal fatigue.
The results of the evaluations in the classrooms demonstrated the need for noise control in these environments, in order to align them with the requirements of good oral communication. The simulations revealed that it is possible to improve the façade insulation by substituting ordinary windows (about 5 mm thick) for double paned windows. The amendment of ceiling finishing materials proved efficient, since it resulted in a reduction of the RT to values that are adequate or very close to those established by the standards listed in Table 7. As for speech intelligibility, the STI classification of "good" to "excellent" was only achieved through a combination of reduced background noise and reduced RT inside the classrooms.

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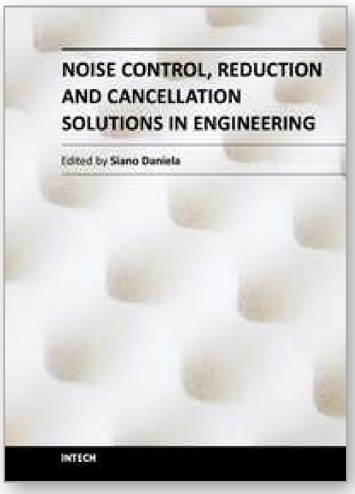

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Noise has various effects on comfort, performance, and human health. For this reason, noise control plays an increasingly central role in the development of modern industrial and engineering applications. Nowadays, the noise control problem excites and attracts the attention of a great number of scientists in different disciplines. Indeed, noise control has a wide variety of applications in manufacturing, industrial operations, and consumer products. The main purpose of this book, organized in 13 chapters, is to present a comprehensive overview of recent advances in noise control and its applications in different research fields. The authors provide a range of practical applications of current and past noise control strategies in different real engineering problems. It is well addressed to researchers and engineers who have specific knowledge in acoustic problems. I would like to thank all the authors who accepted my invitation and agreed to share their work and experiences.